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INTEGRATEABLE BAND FILTER USING WAVEGUIDE GRATING ROUTERS

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INTEGRATEABLE BAND FILTER USING WAVEGUIDE GRATING ROUTERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application is related to U.S. Patent No. 5,745,618 entitled

5 "Optical device having low insertion loss", issued April 28, 1998, which is

incorporated herein by reference in its entirety. This patent application is also

related to U.S. Patent 6,603,898 entitled "Apparatus and method for achieving a

smooth spectral response optical filter", issued August 5, 2003, which is also

herein incorporated by reference in its entirety.

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FIELD OF THE INVENTION

This invention relates to the field of optical band filters and, more

specifically, to integrated optical band filters having reduced ripple.

15 ## BACKGROUND OF THE INVENTION

A band filter is a device that is able to separate an incoming optical

spectrum into bands (i.e., when used as a demultiplexer) or combine separate

optical bands into an output optical spectrum (i.e., when used as a multiplexer),

ideally with sharp passband corners. Band filters are useful in both dense (D) and

20 coarse (C) wavelength-division multiplexed (WDM) systems. In DWDM systems,

band filters are typically used for de/multiplexing with a high spectral efficiency or

for permitting the use of narrowband optical amplifiers, dispersion compensators,

add-drop filters, etc. In CWDM systems, band filters are typically used for

de/multiplexing without transmitter temperature control.

25 In current optical systems, a substantial portion of the implemented band

filters are based on thin-film interference filters. Thin-film interference filters

typically have very low losses however, they require expensive hermetic packages

and tedious hand assembly. Thin-film interference filters also typically exhibit

significant chromatic dispersion, they require more than ten cavities to achieve

sharp passband corners, and they typically require a cascade to demultiplex more than two bands.

Band filters based on bulk gratings have also been proposed. This type of band filters can be dispersion-free and can de/multiplex more than two bands
5   without a cascade, however, they exhibit more loss than their thin-film counterparts. Bulk grating band filters also comprise large form factors, and, like thin-film filters, require expensive hermetic packages and tedious hand assembly.

Finally, band filters based on planar lightwave circuits (PLCs) have also been proposed. Silica waveguide PLCs do not require hermetic packaging and
10   they typically do not require optical alignment (except for an automatable fiber attachment). PLC band filters are capable of being dispersion-free, and they can readily have sharp passband corners. However, the previously proposed band filters based on PLCs (also known as MZI-based filters) become exceedingly large in form factor and are very demanding to de/multiplex more than four bands and/or
15   to achieve sharp passband corners.

SUMMARY OF THE INVENTION

The present invention advantageously provides a compact easy to fabricate reduced ripple band filter that is capable of being constructed in planar lightwave
20   circuit (PLC) technology.

In one embodiment of the present invention, a band filter of the present invention includes two waveguide grating routers (WGRs) connected by a plurality of waveguides having substantially equal path lengths within each set. The connecting waveguides are spaced at their connection to each waveguide grating
25   router such that optical signals having overlapping frequency ranges are propagated through adjacent waveguides and such that optical signals with predetermined optical frequency ranges are routed to selected, respective output ports. In one embodiment of the present invention, each of the sets of connecting waveguides are contiguous at their connection to a first waveguide grating router

and have increased gaps between bands at their connection to a second waveguide grating router.

In an alternate embodiment of the present invention, a planar lightwave circuit includes at least two substantially identical band filters of the present invention constructed on a single chip to save cost. In one embodiment, the planar lightwave circuit has a size equal to 8.7 cm × 1.0 cm.

BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 depicts a high level block diagram of one embodiment of a band filter in accordance with the present invention;

FIG. 2 depicts a more detailed diagram of the band filter of FIG. 1 constructed on a single chip in planar lightwave circuit (PLC) technology;

FIG. 3a graphically depicts the measured transmissivities for the upper band demultiplexer of the PLC chip of FIG. 2;

FIG. 3b graphically depicts the measured transmissivities for the lower band demultiplexer of the PLC chip of FIG. 2;

FIG. 4a graphically depicts the measured transmissivity of the central band of the lower band demultiplexer of the PLC chip of FIG. 2; and

FIG. 4b graphically depicts the chromatic dispersion of the central band of the lower band demultiplexer of the PLC chip of FIG. 2.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION OF THE INVENTION

Although various embodiments of the present invention herein are being described with respect to a 1 x 3 optical band filter, it will be appreciated by those skilled in the art informed by the teachings of the present invention that the

concepts of the present invention are applicable to band filters comprising substantially any number or combination of inputs and outputs.

FIG. 1 depicts a high level block diagram of one embodiment of a band filter in accordance with the present invention. The band filter 100 of FIG. 1 illustratively

5   comprises one input waveguide 105, an input waveguide grating router (WGR) 110, a plurality of connecting waveguides 115, a plurality of dummy waveguides 117, an output WGR 120 and three output waveguides 125_1, 125_2 and 125_3 (collectively output waveguides 125). Although in FIG. 1, the band filter 100 is being depicted and described as comprising one input waveguide 105 and three

10   output waveguides 125_1, 125_2 and 125_3 and as such functioning as a demultiplexer, a band filter in accordance with the present invention may also be used in reverse (i.e., using the three waveguides 125_1, 125_2 and 125_3 as the input and the one waveguide 105 as the output) and function as a multiplexer.

The band filter 100 of the present invention is a novel arrangement of two

15   substantially perfectly sampled waveguide grating routers (WGRs). Such sampling is described in U.S. Patent 6,603,898 entitled "Apparatus and method for achieving a smooth spectral response optical filter", issued August 5, 2003 to Christopher R. Doerr, which is herein incorporated by reference in its entirety. Briefly stated, the design technique minimizes the loss and ripple in the spectral response of an

20   optical filter formed using a pair of gratings connected by an array of optical elements. The smoothest spectral response is achieved for a given set of connecting waveguides by choosing the number of grating arms less than or equal to filling the star coupler central Brillouin zone made by the set of connecting waveguides resulting in the connecting waveguides neither substantially over- or

25   under-sampling the optical spectrum from the waveguide gratings. Exactly filling the Brillouin zone with the grating arms minimizes the loss, and so is the preferred choice.

Referring back to FIG. 1, the plurality of connecting waveguides are illustratively divided into three sets of waveguides 115_1, 115_2 and 115_3. Each of

30   the sets 115_1, 115_2 and 115_3 of the plurality of connecting waveguides 115 of the

band filter 100 have substantially equal path lengths within a wavelength band. More specifically, a band filter in accordance with the present invention comprises a number of individual sets of connecting waveguides at least equal to the number of bands that an input optical spectrum is to be separated into by the band filter.

5 Each of the sets 115_1, 115_2 and 115_3 of the plurality of connecting waveguides 115 are comprised of waveguides having substantially equal path lengths within the specific wavelength band that they are intended to separate and propagate. In FIG. 1, for simplifying the diagram, the upper set of connecting waveguides 115_1 is depicted as being curved, the center set of connecting waveguides 115_2 is

10 depicted as being straight, and the lower set of connecting waveguides 115_3 is depicted as being curved.

The inlets of the connecting waveguides 115 are continuous at their connection to the left-side WGR 110 and have gaps between bands at their connection to the right-side WGR 120. Illustratively, the left-side WGR 110 has

15 one input waveguide, and the right-side WGR 120 has as many output waveguides as there are bands (illustratively 3 output waveguides). The output waveguides 125 are spaced by the size of the gaps minus one waveguide spacing, multiplied by the lensing magnification factor of the right-side WGR 120. Except at the gaps between the connecting waveguide sets, the connecting waveguides 115 perfectly,

20 or slightly over-sample the WGR 120 spectra. More specifically, the connecting waveguides are positioned and formed such that optical signals having overlapping frequency ranges are propagated through adjacent waveguides. As such, the number of waveguide grating arms in each WGR 110, 120 is approximately equal to or less than the number of connecting waveguides it would take to fill one WGR

25 diffraction order. This allows the transmissivity through the band filter 100 within a band to be ripple-free. It should be noted that, for optimum performance, the gaps between the bands of connecting waveguides should be an integer number of the connecting waveguide inlet spacing such that the dummy waveguides 117 inserted in the gaps are able to make the mutual-coupling-induced aberrations for all

connecting waveguide inlets substantially identical. However, the gaps do not
have to be an integer of inlet spacing in order for the band filter to operate properly.

FIG. 2 depicts a more detailed diagram of the band filter 100 of FIG. 1
constructed on a single chip in silica-on-silica PLC technology. FIG. 2 illustratively

5   depicts two substantially identical band filters 205, 210, such as the band filter 100
of FIG. 1. In FIG. 2, two band filters 205, 210 are depicted as being constructed on
the single chip to save packaging costs and because a multiplexer and
demultiplexer are often needed in the same location. The band filters 205, 210 of
FIG. 2 are illustratively depicted as functioning as band demultiplexers. The band

10   demultiplexers 205, 210 in FIG. 2 share fiber assemblies in order to save cost.
The size of the PLC chip of FIG. 2 is 8.7 cm × 1.0 cm. Each of the band
demultiplexers 205, 210 in FIG. 2 splits the center (C) and long (L) optical band
into five 17-channel (100-GHz-spacing) bands with dead zones of 3 channels (i.e.,
it is a 17-skip-3 filter). Each band has 10 connecting waveguides (200-GHz

15   spacing), and the gaps between bands at their connection to the output WGR are 4
spacings (i.e., 3 dummy waveguides between bands). The output of the output
WGR has 5 output waveguides spaced by 3 inlet spacings. There are illustratively,
$M = 75$ arms in each WGR, and the WGR free-spectral range is 15200 GHz. The
spectral sampling coefficient, s, for the connecting waveguides is characterized

20   according to equation one (1), which follows:

$$s = \frac{R}{Ma}\frac{\lambda}{n_{fs}b}.$$

(1)

In equation (1) above, R depicts the radius of the free-space region from

25   which the connecting waveguides emanate, λ depicts the wavelength, n_{fs} is the
effective refractive index of the free-space region, M is the number of arms in each
WGR, a is the center-to-center spacing between grating inlets at the free-space
region, and b is the center-to-center spacing between connecting waveguide inlets
at the free-space region. For each of the demultiplexers 205, 210 depicted in FIG.

2, the spectral sampling coefficient, s, for the connecting waveguides ranges from 1.07 to 1.01 from the shortest to the longest wavelength. In comparison, a conventional Gaussian-passband WGR demultiplexer has spectral sampling coefficient of $s \approx 0.5$. A spectral sampling coefficient of $s \geq 1$ results in a

5   substantially ripple-free passband. The values of λ, n_{fs}, and b vary from connecting waveguide to connecting waveguide.

It should be noted that the increased gap between the connecting waveguides at the band boundaries in a band filter may cause the outermost waveguides in each band to experience a slightly different amount of etching during the core

10   definition, which results in these waveguides being no longer perfectly in phase with their neighboring waveguide in the band. This results in ripples at the band edges. To avoid this, in a band filter of the present invention, dummy waveguides are located within the gaps as much as possible while avoiding mutual coupling once the waveguides start bending. Based on simulation results, the waveguide

15   grating arm lengths were adjusted in the design to minimize aberrations due to the connecting waveguide inlet mutual coupling.

To mitigate loss, segmentation is used in the six inner slab-to-waveguide-array junctions. Segmentation is the placement of strips of core running perpendicular to the waveguides with an approximately constant center-to-center

20   spacing but a progressively decreasing width as the distance from the free-space region increases. Such segmentation is described in U.S. Patent 5,745,618 entitled "Optical device having low insertion loss", issued April 28, 1998 to Yuan P. Li, which is herein incorporated by reference in its entirety.

Also, to mitigate fabrication and polarization sensitivities, within each

25   connecting waveguide set, the sum of the lengths of the straight waveguides, the sum of the lengths of the transitions between straight waveguides and curved waveguides, and the sum of the lengths of the curved waveguides (all having the same bend radius) are all individually kept constant from waveguide to waveguide.

In an experiment, the inventor manufactured a PLC chip, such as the PLC

30   chip depicted in FIG. 2, using low-pressure chemical vapor phase deposition

(LPCVD) and reactive ion etching. The PLC chip was diced out, and fiber ribbon assemblies were glued to both sides. Despite the above-mentioned efforts to make the immediate environment for the outermost waveguides in each band the same as the inner ones, the inventor determined after manufacture that the

5   outermost waveguides were slightly too long in path length and an ~0.8 dB ripple was observed on the long-wavelength edge of each band. The inaccuracy was measured by using small chrome heaters on every connecting waveguide. By driving the heaters, it was determined that the outermost waveguides were slightly long in path length. A possible explanation is that the waveguide density is higher

10   for the inner waveguides, and thus there is more etchant available there, causing increased undercutting during the core definition. The outermost waveguides, having less undercutting, would have slightly higher propagation constants, appearing to have longer path lengths.

       To adjust the path lengths of the PLC chip, the respective chrome strips were

15   hyperheated (heating up the waveguides to a temperature high enough to modify the glass) to permanently readjust the path lengths, significantly reducing the ripple. Because this ripple is consistent from device to device and wafer to wafer, it could be corrected in future manufacture and design by slightly shortening the outermost connecting waveguides in each band.

20   FIG. 3a and FIG. 3b graphically depict the measured transmissivities for the upper 205 and the lower 210 band demultiplexers, respectively, of the PLC chip of FIG. 2. In FIGs. 3a and 3b, the transmissivity of the respective band demultiplexer is plotted versus wavelength. From FIGs. 3a and 3b, it is evident that the connecting waveguides are adapted to provide low-loss propagation of optical

25   signals within one or more predetermined optical frequency ranges. The insertion loss (fiber-to-fiber, including one connector) is < 4.0 dB for the center bands, < 5.0 dB for the low-wavelength band, and < 5.5 dB for the long-wavelength band. The polarization-dependent loss is < 0.15 dB. The 0.3-dB bandwidth is 1670GHz, and the 20-dB bandwidth is 2210GHz, giving a shape factor ($BW_{20dB}/BW_{0.3dB}$) of 1.32.

30   This filter is designed as a 17-skip-3 filter, but with this shape factor it is good

enough to be a 5-skip-0 filter. More specifically, the filter shape of the present

invention is appropriate to have 5 channels per band with one wavelength channel

position that cannot be used between bands. A highly desirable band filter is an *N*-

skip-0 filter. In such a case, no wavelength channel positions are lost. The

5   present invention may be used to create a filter, such as an 8-skip-0 filter.

        FIG. 4a and FIG. 4b graphically depict the measured transmissivity and

chromatic dispersion, respectively, of the central band of the lower band

demultiplexer 210 of the PLC chip of FIG. 2. The chromatic dispersion magnitude

for the lower band demultiplexer 210 is extremely small, <1 ps/nm across a band.

10   The adjacent band crosstalk is <-23 dB, and the nonadjacent band crosstalk is <-

34 dB. The adjacent crosstalk is relatively high because all the bands, after being

split apart by the connecting waveguides, reenter a single WGR. Assuming an

optical signal propagating from left to right through the device, adjacent bands are

focused onto the output waveguides in the right-side WGR, which are relatively

15   closely spaced. Errors in the right-side WGR will cause sidelobes that look like the

adjacent bands. Assuming an optical signal propagaing from right to left, adjacent

bands are focused slightly off from the input waveguide, however these bands are

shifted away from the band by the gap spacing. Thus errors in the left-side WGR

cause sidelobes that also look like the adjacent bands but shifted by the gap

20   spacing. Nevertheless, with better mutual-coupling-induced aberration correction

and improved process control, an adjacent crosstalk <-30 dB is achievable.

        While the forgoing is directed to various embodiments of the present

invention, other and further embodiments of the invention may be devised without

departing from the basic scope thereof. As such, the appropriate scope of the

25   invention is to be determined according to the claims, which follow.